Fundamental thermal fluid physics of high temperature flows in advanced reactor systems

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Funding agency: DoE NERI program, 1999-2002

The **objective** of this laboratory/university/industry collaboration of coupled computational and experimental studies addresses fundamental science and engineering to develop supporting knowledge required for reliable approaches to new and advanced reactor designs for improved performance, efficiency, reliability, enhanced safety and reduced costs and waste and for small reactors for remote power and hydrogen generation. It ***provides basic thermal fluid science knowledge*** to develop increased understanding for the behavior of fluid systems at high temperatures, application and improvement of modern computation and modeling methods and incorporation of enhanced safety features. The project promotes, maintains and extends the nuclear science and engineering base to meet future technical challenges in design and operation of high efficiency reactors, low output reactors and nuclear plant safety; it brings recognized thermal fluid mechanics authorities, Profs. Pletcher, Vukoslavcevic and Wallace and their students, into the nuclear science and engineering research community.

This basic thermal fluids research applies first principles approaches (Direct Numerical Simulation and Large Eddy Simulation) coupled with experimentation (heat transfer and fluid mechanics measurements). Turbulence is one of the most important unresolved problems in engineering and science, particularly for the complex geometries occurring in advanced reactor systems and their passive safety systems. ***Prof. Pletcher*** extended LES to generic idealizations of such geometries; ***Profs. Satake and Kunugi*** supported these studies with DNS. ***Profs. Wallace and Vukoslavcevic*** developed miniaturized multi-sensor probes to measure turbulence components in high temperature flows. ***INEEL*** conducted experiments to obtain fundamental turbulence and velocity data for generic idealizations of the complex geometries of advanced reactor systems. ***Prof. Jackson*** conducted measurements of the effects of buoyancy forces on flow in circular tubes, channels and annuli. ***Drs. Shenoy and Baccaglini at General Atomics*** provided thermal-hydraulic data needs for Modular Helium Reactors and reviewed the computational techniques and supporting results to determine their applicability to gas-cooled reactor operation.

The unique INEEL Matched-Index-of-Refraction flow system, the World's largest such facility, was applied for the first time to obtain fundamental data on flows through complex geometries important in the design and safety analyses for advanced reactors (Figure 1). Successful completion of the ***study provides the following new fundamental and engineering knowledge***, which was not available in the literature:

- Time-resolved data plus flow visualization of turbulent and laminarizing phenomena in accelerated flow around obstructions (spacer ribs) in annuli.

- Application of DNS and LES for the first time to complex turbulent flows occurring in advanced reactors
- Fundamental data of internal turbulence distributions for assessment and guidance of computational thermal fluid dynamics (CTFD) codes proposed for design and safety analyses for advanced gas-cooled reactors

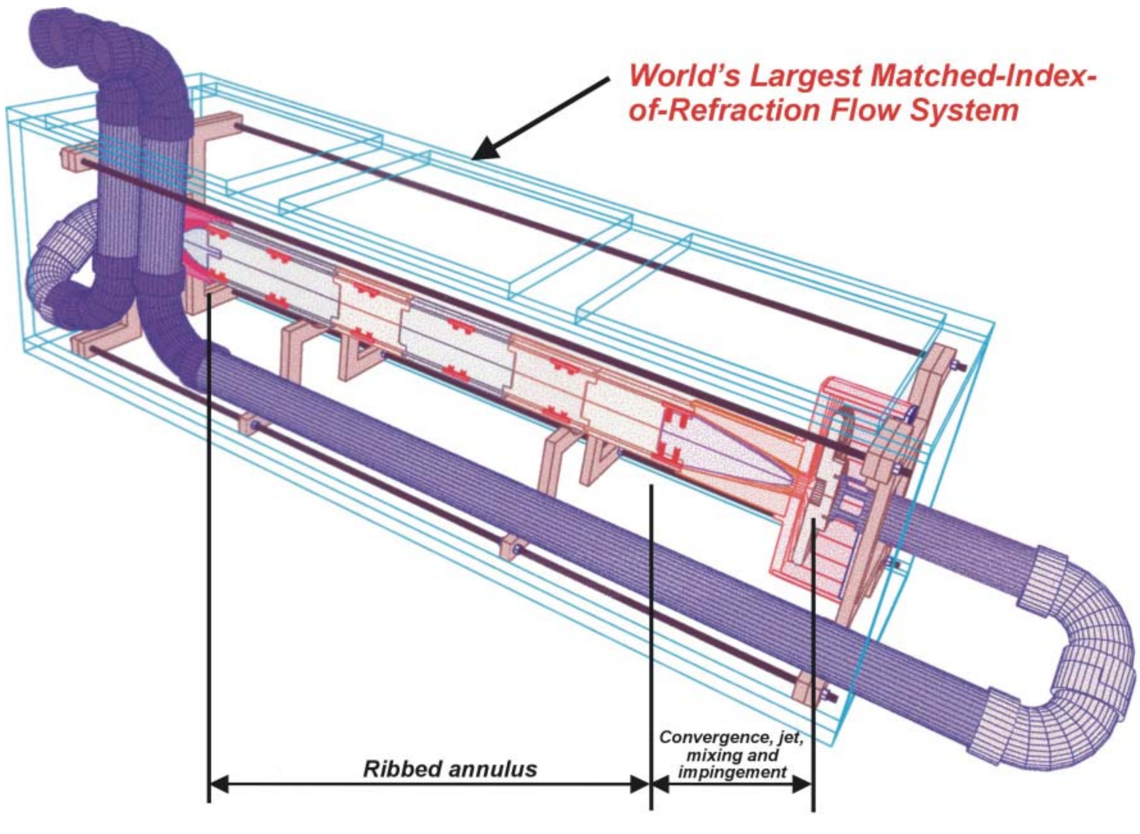

Fig. 1. Overview of experiment in MIR flow system.

Task A: Heat transfer and fluid flow in advanced reactors, Drs. A. S. Shenoy and G. Baccaglini, General Atomics GA identified six areas of thermal hydraulic phenomena in which the application of Computational Fluid Dynamic techniques can improve the safety of advanced gas cooled reactors. Dr. Baccaglini provided performance parameters for normal and emergency operations to support the planning of computational techniques and experiments. He and Dr. Shenoy interacted with the analysts and reviewed the collaborators's tasks to assure that the results of this project will be applicable to the improvement of reactor safety.

Task B: Complex flow measurements, INEEL The goals of the INEEL experimental portion of the study are to provide fundamental measurements to answer the scientific needs identified in the proposal and to guide code development and assess code capabilities for treating generic forced convection problems in advanced reactors. Flow through idealized, complex reactor geometries was examined without complicating thermal phenomena; laser Doppler anemometry was employed with INEEL's unique Matched-Index-of-Refraction (MIR) flow facility to determine the velocity and turbulence fields. The innovation of the INEEL MIR system is its large size compared to earlier systems; it provides means for measurements for the portion of the study dwelling on forced convection in complex reactor geometries.

INEEL conferred with General Atomics staff to identify generic features of complex advanced reactor geometries and to determine parameter ranges of interest. Conceptual experimental models were developed for laser Doppler velocimeter measurements in the large INEEL MIR flow system to examine flow in complex core geometries (ribbed annular cooling channels and control rod configurations) and in the transition from cooling channels to formation of jets issuing into a plenum. Two experimental models have been used. These experiments addressed two thermal/hydraulic phenomena selected by GA: (1) normal operation at full or partial loads and (2) loss of forced reactor core cooling.

The first experimental model was a ribbed annulus forming an annular jet exhausting into the larger surrounding test section of the MIR flow system. The initial MIR experiments were aimed at obtaining benchmark data to test the capabilities of CFD codes to handle ribbed annular geometries without the complications of turbulent transport (i.e., laminar flow requiring no turbulence modeling, although localized turbulence may exist within eddies shed from the spacer ribs). Streamwise-periodic flow was observed away from the ends of the model. Preliminary flow visualization measurements were obtained by injecting small air bubbles into the oil flow in the annulus. These observations, recorded in photographs, outlined the eddy which forms behind the spacer rib due to separation and recirculation.

LDV data for two velocity components were obtained at $Re_{D,h} = 4\dot{m} / (\Pi(D_o+D_i)\mu) \approx 1120$ as radial, axial and circumferential profiles of U, V, u′ and v′ as well as spectral analyses. These conditions correspond to some stages during a pressurized cooldown (LOFA) event. The measured radial profile of the streamwise velocity component away from the ribs has been compared to the analytical solution for laminar flow in an axisymmetric annulus (i.e., without ribs). With a radius ratio of about 0.82, the analytic solution is close to that of a parallel plate duct which would have $U/V_b = 1.5$ at the centerplane (Figure 2). Between ribs (circumferentially) the flow must accelerate due to the blockage of the ribs. The shape of the measured profile agrees with the analytic prediction for a bulk velocity about twelve per cent higher than the value which applies in the space between the ribs axially.

As expected, the LDV data showed that a slow recirculating region formed behind a rib. This region could be expected to produce a "hot spot" if the inner surface were heated. However, frequency spectra for the flow in this region demonstrated an oscillating flow characteristic of eddy shedding from a circular cylinder. Increased levels of fluctuations u′ and v′ were also observed. Consequently, at these flow conditions a "hot spot" would likely be ameliorated by the oscillating turbulent flow (and thermal conduction in the solid rod). Turbulence is also indicated in profiles from radial traverses obtained at positions downstream of the spacers. For (long) circular cylinders, eddy shedding at a non-dimensional frequency $St \approx 0.2$ occurs for $Re_D >$ about 50. For the long rectangular spacer, $St = wf/V_b \approx 0.15$ and $Re_w = V_b w/\nu \approx 1000$, where w is the average width of a rib in the circumferential direction.

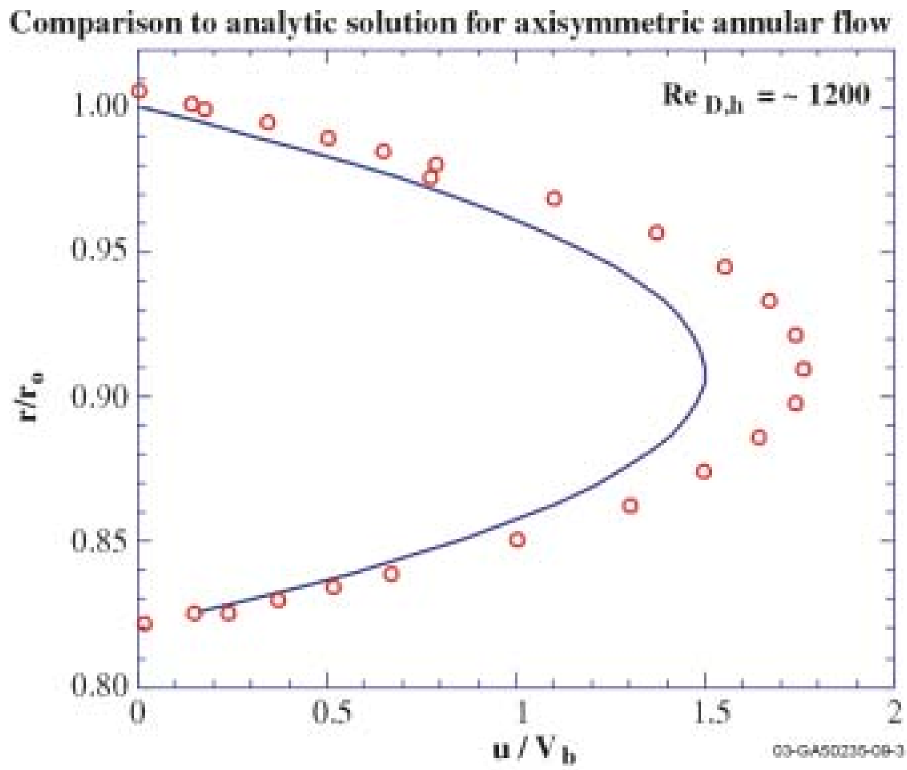

Fig. 2. Comparison of measured velocity profile in a ribbed annulus to analytical prediction for laminar flow in an axisymmetric annulus at the same flow rate [Kays, 1966].

Calculations for the conditions of the experiment were conducted using a general-purpose, commercial CFD code. These efforts demonstrated the difficulty in applying CFD codes to this three-dimensional geometry.

The second experiment addressed flow in coolant or control rod channels and an idealized two-stage jet transition from generic coolant channels to a plenum. It is a combined experiment focusing on flow in the ribbed annulus upstream and the first stage of this geometric transition, a jet issuing from a converging flow simulating the exit from cooling channels into a collecting plenum (Figure 1). The circular annulus has a nominal outer diameter of about 150 mm (6 in.) and inner diameter of about 135 mm (5.4 in.). Model length is about 1.5 meters with five periodic cells formed by the spacer ribs. Four ribs are distributed radially around the circumference as for a GA control rod. These sets are spaced longitudinally with pitch p/s of about forty. The ribs have widths w/s of about two and lengths L/s of about ten.

Flow visualization experiments were conducted for flow entering, within and exiting the impingement chamber of the apparatus using air bubbles injected in the inlet piping. The flow patterns and streamlines recorded compare closely to those obtained earlier using water flow through a thin planar model of the chamber [McCreery, Pink and McEligot, 2002]. As expected, the flow remained attached further along the convergence than in the planar model since the cross section remained constant, giving a favorable pressure gradient, rather than diverging.

Measurements for the flow in the annulus were completed with our LDV system. Two-component (axial and radial) LDV measurements were obtained in the ribbed annulus at Re ≈ 6900, based on the hydraulic diameter between the ribs axially. Data were obtained in cells 3, 4 and 5 at axial positions halfway between spacers to test the streamwise periodicity of velocity profiles. The flow in the third cell was considered to be representative of the streamwise-periodic pattern, so most measurements were concentrated there. Data were obtained along axial and radial traverses, at locations downstream from spacer ribs and furthest removed from the spacer ribs, both horizontally and circumferentially (Figures 3 and 4). The circumferential variation of streamwise velocity was measured at a constant mid-annular radius at positions midway between spacer ribs in the axial direction. The accelerating flow between the ribs induced reductions in the streamwise velocity fluctuations near the wall and in the central region (radially) and increases were observed in the subsequent decelerating flow (Figure 4). The consequent reduction and enhancement of heat transfer parameters (respectively) would pose challenges to turbulence models typically used in commercial codes so numerical predictions for this case could be misleading.

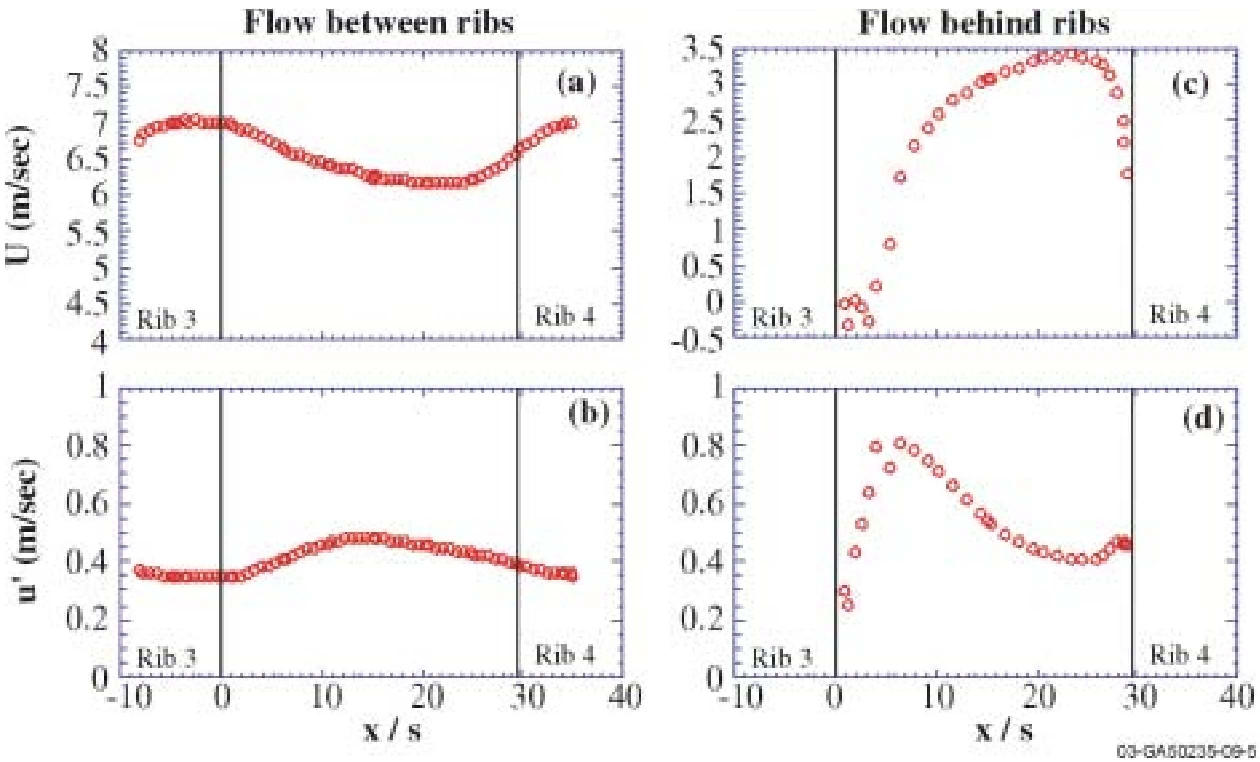

Fig. 3. Axial profiles of mean velocity and fluctuations (a,b) away from spacer ribs and (c,) along "centerline" downstream of a rib, Re ≈ 6900.

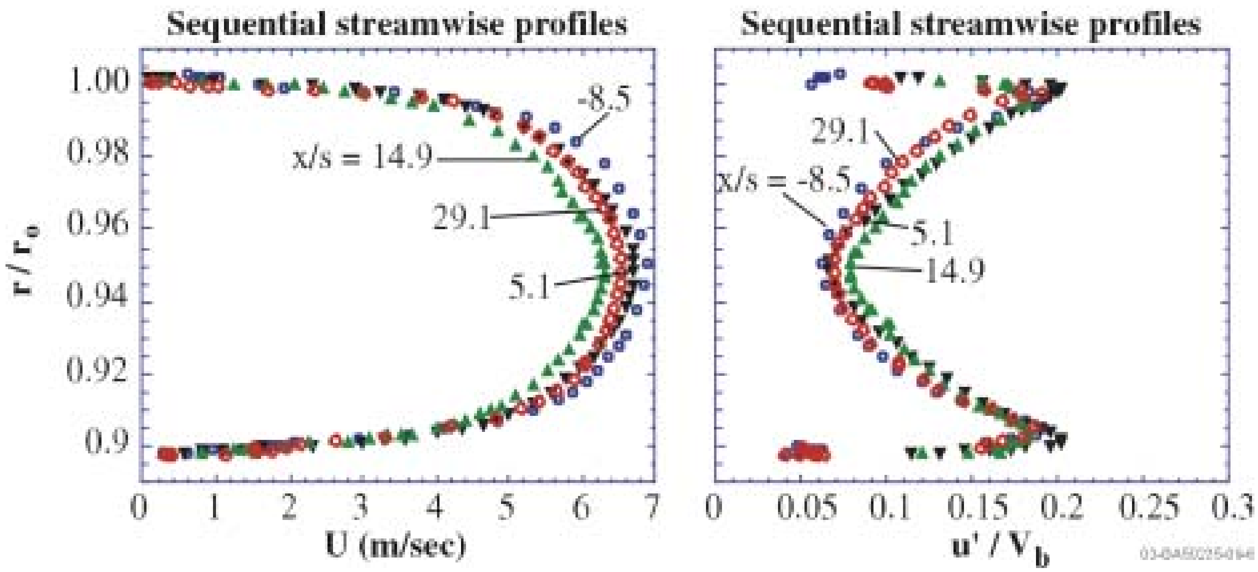

Fig. 4. Radial profiles along "centerplane" circumferentially between ribs, (a) mean streamwise velocity and (b) root-mean-squared streamwise velocity fluctuations.

Task C: Direct Numerical Simulation (DNS) development, Prof. T. Kunugi / Kyoto U. and Prof. S.-i. Satake / Tokyo Univ. Science Profs. Satake and Kunugi are developing DNS for use in high temperature gas (or superheated vapor) flows with transport property variation. Their results assist evaluation of sub-grid-scale models used in LES and of other CFD approaches and will also help in the interpretation of hot wire measurements in these conditions.

They have successfully applied their DNS code for flow in circular tubes with strongly varying gas properties to the conditions of Run 445 from the experiments by Shehata and McEligot [1998]. In that run the flow entered the heating section as a fully-developed turbulent one and, due to the strong heating (causing property variation and acceleration), was effectively laminarized within about twenty-five diameters [Satake et al., 2000].

DNS calculations were next initiated for Run 635, at a higher Reynolds number and lower heating rate, conditions which other investigators have found difficult to predict adequately with so-called advanced turbulence models. In addition, calculations were initiated for Run 618, at the same inlet Reynolds number as Run 635 but with a lower heating rate. Run 618 represents a turbulent flow that has reduced heat transfer parameters due to effects of property variation but no apparent laminarization; as such it is comparable to normal operating conditions for cooling channels in a GA advanced gas-cooled reactor. Runs 635 and 445 correspond to conditions expected to occur as the Reynolds number decreases during a transient LOFA. With these DNS calculations, it appears that the sub-turbulent state of Run 635 is easier to calculate than that of turbulent Run 618. Calculations for Run 635 are essentially complete but Run 618 requires more computation to converge.

Task D: Large Eddy Simulation (LES) development, Prof. R. H. Pletcher, Iowa State The main thrust of this task is to extend LES methodology to a broader class of flows with heat transfer, particularly flows characteristic of those occurring in modern nuclear reactors. Prof. Pletcher's earlier LES channel flow code treated strongly varying gas flows with buoyancy effects. He and his graduate students modified this code to apply to circular geometries, such as tubes and annuli. Several cases were addressed:

- Horizontal turbulent channel flows with buoyancy
- Vertical turbulent channel flows with buoyancy
- Circular tube with buoyancy
- Annular flow, isothermal validation case
- Annular flow, case with inner wall heating
- Ribbed annulus, isothermal case for comparison with INEEL experiments

Most calculations account for variation of gas properties - thermal conductivity, viscosity and density - with temperature and for buoyancy effects. The tube geometry corresponds to coolant channels in GA prismatic reactors and to an MIT concept for gas-cooled fast breeders. The annular geometry occurs in control rod geometries in GA reactors and in the HTTR and comparable reactors.

LES results have been obtained for vertical upward flow of air in a channel heated on one side and cooled on another [Lee and Pletcher, 2001; Dailey, Meng and Pletcher, 2003]. Such a channel flow corresponds closely to flow in an annular passage of large radius ratio, e.g., the vertical annular flow between the core barrel and the reactor vessel wall or fuel coolant passages of the Japanese HTTR. One observes that buoyancy induces a "laminarizing" effect near the heated wall, reducing the turbulent kinetic energy, Reynolds stress and Nusselt number. However, the friction coefficient and temperature fluctuations are increased near this wall. The property variations modify the local Reynolds number; this modification may partially explain observed structural changes. This work is the first known LES study of a vertical flow accounting for buoyancy and variations in fluid properties.

In progress are some comparisons with the mixed convection data obtained by our partners at CEA Grenoble for upward turbulent flow between vertical parallel plates at different wall temperatures [Moro, Saez and Hopfinger, 1998]. This situation is comparable to LES code predictions mentioned above. Comparisons for their isothermal flow at a Reynolds number of 6775 based on the mean velocity and channel half-width have been completed and show reasonable agreement.

Additional comparisons have been made with the measurements of Shehata and McEligot for heat transfer to strongly-heated turbulent flow in a vertical pipe [Xu, Lee and Pletcher, 2002]. Their Runs 445, 618 and 635 were considered. Comparisons have been made with the data taken at $x/D = 14$ and 25. Fairly good agreement has been observed between the large eddy simulations and the data. The simulations are based on a quasi-developed assumption. Step-periodic boundary conditions for temperature are used in the streamwise direction. To initiate the simulations, the experimentally-observed values of the wall temperature distributions and the local Reynolds numbers were employed. With high heating rates, property variations cause the streamwise change in temperature from inlet to outlet of the computational domain to be a function of the radial position in the pipe. The level of agreement between simulations and experiment was found to depend on how this radial variation is represented.

In the case where a series of fairly short (in terms of hydraulic diameters) ribbed spacers are used in an annulus, as in the experiments of Task B and the coolant channels for GA control rods and HTTR fuel elements, it is possible to embed a set of ribs within a quasi-developed, spatially-periodic computational region. This approach enables the simulation of the complete flow field around the ribbed region and should provide valuable detailed information about the flow including information that would be difficult to achieve experimentally. Such a procedure was implemented. Simulations were made for Reynolds numbers of 500 and 1200 based on the bulk velocity and hydraulic diameter both evaluated for the unobstructed portion of the annulus. The general flow pattern around the spacers, as seen in contours of mean streamwise centerline velocity and plots of streamlines, corresponds to the experimental observations. Measured and computed profiles of the mean streamwise velocity midway (axially and circumferentially) between the spacers showed quite good agreement.

Task E: Multi-sensor probe development, Profs. J. M. Wallace and P. Vukoslavcevic, U. Maryland Prof. James M. Wallace and Visiting Prof. Petar Vukoslavcevic (from the University of Montenegro) developed miniaturized multi-sensor probes to measure instantaneous turbulence components in high temperature flows. These probes were developed for employment by INEEL and other collaborators to measure fluctuating velocity components and temperature in high temperature gas flow through vertical pipes and channels for assessment of predictions and to understand the fundamental effects of this heating on the physics of the flow.

Two versions of test probes were designed and constructed, as well as a calibration test facility. The calibration facility for the hot-wire probes that are to be operated at high temperature has been designed to provide a variable and uniform velocity and temperature flow field in the speed range of 0.5-15 m/s and temperature range from ambient room temperature to over 600°C. The speed and temperature profiles are uniform over most of the nozzle exit area for different speeds and the temperature range. The variation is less than one per cent in the region in which the probe, temperature and velocity sensors are tested and calibrated.

In order to determine the best probe geometrical arrangement and sensor separation, several test probes were constructed and tested. Based on experiments, the best sensor arrangements were chosen for final boundary-layer type probes. The final boundary layer probe types are similar to the test types. The main difference, because they must be positioned as close as possible to the wall, is that they also have an additional prong designed to be used as a spatial distancer. They have two hot wire sensors for velocity components and a single "cold" wire sensor for instantaneous temperature. The diameter of the sensor "volume" is about one millimeter. For calibration, two nonlinear algebraic equations have been derived. Each has seven constants to be determined. A simple numerical algorithm has been developed to solve those two equations for the case of known fluid temperature.

Two operating parameters have to be optimized for a probe of given geometrical arrangement and flow conditions: the overheat ratio of the velocity sensors and the current of the temperature sensor. The probes have been designed to be used in a wide range of flow condition (speed and temperature) and the choice of these two parameters should be in accordance with a given flow condition. The first flow to be investigated with this probe was at the University of Manchester (Task F) with a low speed (0.9 to 3 m/s) and moderate temperature (up to 200°C). Calibration coefficients were determined for these conditions and responses of the velocity component and temperature measurements were examined for ranges of velocity, temperature and angular orientation. It was found that the probe is capable of measuring simultaneous turbulent velocity fluctuations at low speeds and moderate temperatures, i.e., for cases corresponding to the experiment at the University of Manchester, with an accuracy of order of one per cent. These conditions are considered to be very complex at low speed, due to mutual sensors influence and deviation of the cooling law.

The principal application of such hot-wire probes within the scope of this NERI project is to measure turbulence very close to heated walls. Thus, it is important to be able to extend the velocity range to below 0.9 m/s, if possible. Two approaches have been tested. The first is to reduce the sensor temperature for the case where the air temperature is expected to be low, as in the COPPEC facility for free or mixed convection flows of our partners at CEA Grenoble. For air temperatures of about 100°C, the approach utilized in the research mentioned above can be extended to speeds as low as 0.4 m/s. The other approach is to reduce the diameters of the velocity sensors to about one micron. Preliminary results show that the minimum speed can be reduced to 0.4 m/s at temperatures as high as 200°C.

Task F: Mixed convection, Prof. J. D. Jackson, U. Manchester Prof. Jackson and colleagues at Manchester conducted three experiments emphasizing buoyancy effects. The first obtained data on velocity in strongly heated air flow through a vertical heated pipe under conditions of mixed convection to determine the effects of buoyancy forces combined with property variation on local mean velocity and turbulent fluctuations. A second experiment provided data on the influence of the temperature dependence of fluid properties and buoyancy on heat transfer for the case of air flowing in a passage of annular cross section with a heated core. In the third experiment local mean velocities and turbulent fluctuations were measured using LDV in water flowing in a vertical passage of annular cross section with a heated core under conditions of mixed convection. Data were also obtained in a wide vertical channel flow with heating from one side.

Prof. Jackson and his colleagues operated a circular tube test facility with a vertical, heated section providing either specified distributions of heat flux or temperature along the tube with air flow in either the upward or downward direction. The combination of flow range and tube diameter allows measurements that are either buoyancy-affected or predominantly buoyancy-free. Their local Nusselt number data for mixed convection show very clear evidence of the importance of the thermal boundary condition on mixed convection heat transfer and that severe impairment of heat transfer can occur in a variety of ways. Using a Pitot-tube/thermocouple probe and the miniature multi-sensor probe of Profs. Vukoslavcevic and Wallace (Task E), they obtained measurements of velocity and temperature profiles in the radial direction near the exit for the upward flow case under buoyancy-influenced conditions at Reynolds numbers from 6,000 to 20,000.

A comprehensive programme of experiments to study the effects of property variations and buoyancy on local heat transfer with upward and downward gas flow has been completed using the annular facility. Some main results are as follows.

- An empirical correlation, including the thermal entry region, has been obtained for heat transfer under conditions of negligible influence of buoyancy
- The criterion for buoyancy influences to have a significant effect on heat transfer in the annulus has been found to be that the buoyancy parameter, $Bo^* = Gr^*/(Re^{3.425} Pr^{0.8})$, must be greater than about 5×10^{-7}. When the Re and Gr* are such that Bo*

exceeds that value, differences are evident between the results for upward and downward flow under otherwise identical conditions.

- For descending flow (the buoyancy-opposed case) Nusselt number is greater than for ascending flow (the buoyancy-aided case). This behaviour is similar to that found with circular tubes.
- For descending flow the effectiveness of heat transfer is always enhanced in relation to that evaluated at the same value of Reynolds number and core-to-bulk-temperature ratio using the correlation equation for forced convection. The enhancement of heat transfer in the present buoyancy-opposed experiments using an annulus is less strong than for circular tubes.
- For values of Bo* of about 10^{-3} the upward and downward flow data come together. The flow is buoyancy dominated. Under such conditions Nusselt number is almost independent of Reynolds number and varies with Grashof number as in heat transfer by free convection.

The third of the three investigations which Prof. Jackson and his colleagues at Manchester have contributed to this NERI project was a study of the influence of buoyancy on turbulent flow and heat transfer in the case of water flowing through a vertical passage of annular cross section having a uniformly heated core and adiabatic outer casing [Xu, 2002]. Measurements of velocity, turbulence and heat transfer were made under conditions of forced convection (negligible buoyancy influence) and also mixed convection (covering a range of buoyancy influence from weak to very strong) with both upward and downward flows. The results provide direct confirmation of the mechanism by which turbulence production in heated vertical passages is either reduced or increased due to the mean flow field being distorted by the influence of buoyancy, causing turbulent diffusion to be either less effective or more effective and turbulent heat transfer to be either impaired or enhanced in relation to that for conditions of forced convection. Results of computational simulations of the experiments -- using a developing flow formulation which takes account of variable properties and buoyancy influence and incorporates the low-Reynolds-number k-ε turbulence model of Launder and Sharma [1974] -- were also compared directly with measurements of velocity, turbulence and heat transfer.

Recognition and technology transfer Prof. Shin-ichi Satake, Tokyo University of Science, received the 1999 JSME Outstanding Young Scientist award from the Japan Society of Mechanical Engineers, for his study on elucidation of characteristics of heat and fluid flow and construction of a data base in a turbulent pipe flow via DNS. Prof. Richard H. Pletcher, Iowa State U., was named a Life Fellow of American Society of Mechanical Engineers and Prof. Dr. Donald M. McEligot, INEEL, was selected to be a member of the US Scientific Committee for the 12th International Heat Transfer Conference held in Grenoble in August 2002. Prof. J. Derek Jackson was appointed as an Honorary Professor at the University of Manchester and an Honorary Visiting Professor at UMIST.

The Principal Investigator, Prof. Dr. Donald M. McEligot, received from the Idaho Academy of Science its annual award as their Distinguished Scientist for 2002. Prof. James M. Wallace of the University of Maryland has been elected to be the Vice-Chairman of the Fluid Dynamics Division of the American Physical Society; the incumbent of this position automatically is promoted to Chairman in a later year. Prof. Shin-ichi Satake of Toyama University was awarded a faculty position at the Tokyo University of Science.

At the 12th International Heat Transfer Conference, Prof. Tomoaki Kunugi of Kyoto University received a 2002 International SFT Award from the Société Francaise de Thermique to recognize and encourage his achievement in heat transfer research.

The ***key results*** of the present fundamental study are the publications and presentations to the thermal fluids community. Since August 1999, the project collaborators have had twenty-two archival papers published or in press, forty-nine conference presentations and twenty invited presentations relating to this collaborative NERI project. They also have fifty publications and presentations on other topics.

Accomplishments The overall accomplishments during the project may be summarized as follows:

- GA identified areas of concern and provided support in planning required computational techniques and experiments
- DNS of laminarizing and "subturbulent" gas flow completed, turbulent initiated, for circular tubes
- First LES conducted for vertical mixed convection with property variation; channel code extended to circular tubes, annuli and ribbed annuli
- MIR experiment for flow in complex reactor geometry (ribbed annuli) designed, fabricated, tested and employed for LDV measurements
- Three- and four-sensor miniature probes developed, tested, calibrated and operated
- Obtained data for mixed convection with property variation and arbitrary thermal boundary conditions in tubes, channels and annuli
- 22 technical publications, 49 presentations and 20 invited talks related to project
- Brought fluid mechanics authorities and students into nuclear science community

Summary technical report

McEligot, D. M., and thirteen others, 2002. Fundamental thermal fluid physics of high temperature flows in advanced reactor systems. Final technical report INEEL/EXT-2002-1613.

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